

Dynamic Range of Frequency-Selective Response of High- T_c Josephson Detector to Millimeter-Wave Radiation

Vadim Shirotov, Yuri Divin, and Knut Urban

Abstract—We have studied a voltage dependence of the response $\Delta I(V)$ of high- T_c Josephson detector to millimeter-wave radiation as a function of power of incident radiation. $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ grain-boundary junctions with the resistances $R_n = 0.5$ – 1.5 Ohm and the $I_c R_n$ -product in the range 0.16 – 0.25 mV at 80 K have been fabricated for this study. Gunn oscillator with the frequency $f = 86$ GHz and a set of calibrated attenuators with total attenuation of 80 dB have been used for the measurements. The dynamic range, i.e. the range of power of electromagnetic radiation at which the response of the detector is directly proportional to radiation power, was found to be around 40 dB above the noise-equivalent power for frequency-selective response at voltages V near $hf/2e$ and >45 dB for the broadband response at low voltages.

Index Terms—High-temperature superconductors, Josephson junctions, millimeter-wave devices, radiation detectors.

I. INTRODUCTION

JOSEPHSON junctions can be efficiently used in the detectors of electromagnetic radiation in the millimeter and submillimeter ranges [1]. Due to an interaction of external monochromatic radiation with voltage-controlled internal Josephson oscillations, Josephson detectors show a resonance behavior in their response at the junction voltages near $V = hf/2e$. This circumstance gives a possibility to use Josephson detectors for spectral analysis of monochromatic radiation. The dc response of a square-law Josephson detector has a unique feature of additivity, which means that the response of this detector to polychromatic radiation is equal to the sum of the responses to the spectral components of this radiation. Due to this additivity, a square-law Josephson detector can recover not only the spectra, consisting of separate lines, but even arbitrary spectra, using so-called Hilbert-transform technique [2].

Recently, the Hilbert-transform spectroscopy based on high- T_c Josephson detector has been used to measure spectra of transition radiation from relativistic electron bunches at TESLA Test Facility linear accelerator at

DESY (Hamburg) [3]. These measurements have been carried out with low-frequency electronics operating with Josephson detector and individual pulsed time structure of analyzed radiation has not been resolved.

It is of interest for effective bunch diagnostics to make a fast spectrum analyzer that could use one bunch passage for measuring one spectral interval. This approach requires much larger bandwidth of electronics operating with Josephson detector. In this case the noise level will increase as a square root of bandwidth and, to be above it, the intensity of electromagnetic radiation should be increased. In this respect, it is important to know the dynamic range of Josephson detector, i.e. the limits of the intensities of electromagnetic radiation where Josephson junction operates as a square-law detector.

In this paper we report on our study of the dynamic range of the millimeter- and submillimeter-wave detector based on $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ Josephson junction, operating at liquid nitrogen temperature.

II. EXPERIMENT

A. Josephson detector

In order to have a possibility for detection of broadband spectra, it is necessary to make a good coupling of the detector with radiation in a frequency range under investigation. A quasioptical coupling and a frequency-independent antenna on the same substrate with the detector are usually approaches in the short millimeter- and submillimeter-wave range.

A schematic view of a spectrometer with Josephson junction integrated into a cryostat is shown in the Fig. 1.

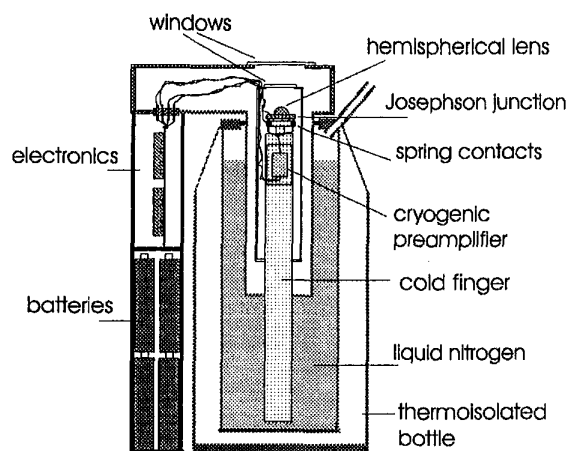


Fig. 2. Compact Josephson detector, operating at LN temperature.

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We used a compact quasioptical cryostat operating at liquid nitrogen temperatures. The grain-boundary $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ Josephson junctions made on 2×140 NdGaO_3 have been used in this work [4]. Josephson junction was placed on a top of a cold finger and an operating temperature of around 80K could be achieved. With one filling of 0.75 l of liquid nitrogen into a cryostat, it was possible to keep the temperature of 80 K on the cold finger during around 7 hours.

External radiation passed through quartz windows and was focused by a hyperhemispherical lens to the junction, integrated into a broadband logoperiodic antenna.

A first cascade of preamplifier operated at LN temperature. We used a low-noise cryogenic amplifier LNA-1618, which has a noise level of $0.16 \text{ nV}/(\text{Hz})^{1/2}$ [5]. A battery power supply was used to reduce the interferences.

B. Experimental set-up

A block-scheme of the experimental set-up is shown in Fig. 2. As a source of radiation we have used a Gunn-oscillator, which operates at 86GHz. We used a millimeter-wave source, because a set of calibrated attenuators was available in this range. Radiation from the source went through a 3mm-waveguide, where it was modulated by PIN-switch diode and attenuated by a set of calibrated attenuators (0 - 20dB and 0 - 60dB). After attenuators radiation went through a horn to a free space and then was focused to the Josephson junction with antenna by parabolic mirror and hiperhemispherical lens. The maximal power of the signal, that went to the free space, was around 3mW.

Analog electronics consisted of a dc-bias circuit and two analog preamplifiers, one for the amplification of the average voltage V on the junction and another - for the response function ΔV . An analog part of the electronics had both input and output buffers to prevent an interferences from the digital part of the set-up.

The response function ΔV was measured by the lock-in amplifier PAR 5110. The bandwidth of response measuring channel was about 1Hz. A signal from a modulation generator with the frequency of 4kHz went to the PIN-switch diode and to the reference input of the lock-in amplifier.

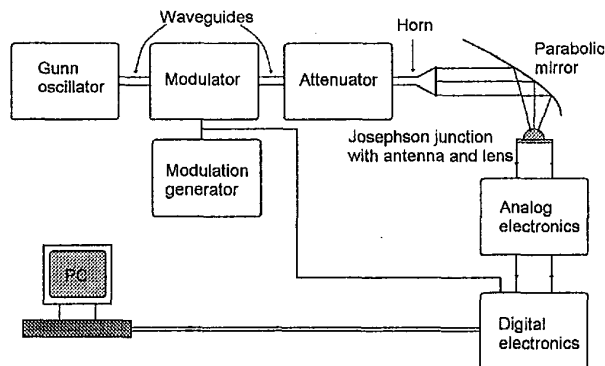


Fig. 2. Experimental set-up for characterization of high-Tc Josephson detector.

We also used a data acquisition system, contained in lock-in amplifier PAR 5110, with DACs and ADCs channels. The output of low-frequency preamplifier was connected to ADC input and the input of the biasing circuit was connected to the output of DAC. The operation of the PAR 5110 was controlled by a personal computer through a GPIB interface.

IV. RESULTS AND DISCUSSION

The thin film $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ grain-boundary Josephson junctions with normal state resistance $R_n = 0.5 - 1.5$ Ohm and $I_c R_n = 160 - 250$ μV have been fabricated for this work.

The responses $\Delta I(V) = I(V) - I_0(V)$, where $I(V)$ and $I_0(V)$ are I - V characteristics of junction with and without radiation correspondingly, have been derived from the measured $\Delta V(V)$ response for these junctions as a function of the intensity of millimeter-wave radiation. The results of the response measurements for one of these junctions with $R_n = 0.7$ Ohm and $I_c R_n = 250$ μV to the 86 GHz-radiation with two different power levels are presented in Fig. 3. Both responses have odd-symmetric resonances at voltages near $hf/2e = 177$ μV .

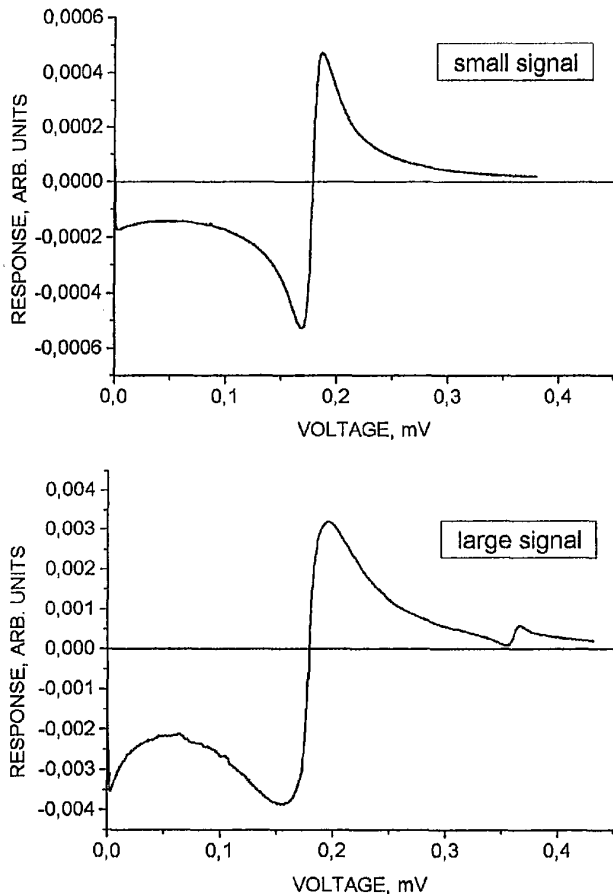


Fig. 3. The responses of Josephson junction to 86GHz- radiation of different intensities.

In the first case, the signal power is small enough to be inside the dynamic range. Here one can see the frequency-selective response at voltages near $hf/2e = 177 \mu\text{V}$ and a nonselective broadband part of the response at low voltages, which is due to the suppression of junction critical current. From this response, using Hilbert transformation one can get an external signal spectrum [2].

In the second case, the signal power is beyond the dynamic range and in spite of the monochromatic radiation there is an additional peculiarity at double voltages. This peculiarity makes the spectrum reconstruction not obvious, because it can be considered as a response to the signal with double frequency. Executing the Hilbert transformation one gets a parasitic line at double frequency.

Josephson junction frequency-selective response amplitude as a function of incident signal power is shown on Fig. 4. On Fig. 4 one can see also the amplitude of broadband response of Josephson junction and the amplitude of peculiarity in the response at the double voltages.

Solid lines show the linear-law behavior in a double logarithmic scale. Arrows show a noise level and a noise equivalent power (NEP) for different response types. So, for the frequency-selective response the $\text{NEP} \approx 7.5 \cdot 10^{-11} \text{ W}/\sqrt{\text{Hz}}$ and for the nonselective response at low voltages the $\text{NEP} \approx 3.8 \cdot 10^{-10} \text{ W}/\sqrt{\text{Hz}}$. These levels might be improved by using better coupling of the Josephson junction with external radiation, but for the study of dynamic range and future measurements at DESY these improvements are not important.

If one determine the high limit of dynamic range as 3dB deviation from the linear-law behavior in the data set, presented in Fig. 4, then the dynamic range for the frequency-selective response is around 43dB (attenuator setting between -76 and -33dB in Fig. 4).

A requirement of the precision reconstruction of the complex broadband spectrum might make more strong conditions for the linearity, than are usually accepted in the theoretical estimations [1], when the signal power should be not more than the power of Josephson oscillations - $I_c V/10$, where I_c is a critical current of the junction.

The amplitude of the peculiarity in the response at double voltages is at least two orders of magnitude less, than the frequency-selective response amplitude inside the dynamic range.

The nonselective response amplitude follows quite well to the linear-law behavior and its dynamic range exceeds 45dB (attenuator settings between 69 and 24dB), in which the measurements were carried out.

If the bandwidth of response measurements increases up to 10MHz, that needs for fast measurements, e.g. for resolving of pulse structure of transition radiation at TESLA Test Facility linear accelerator, then the dynamic range of the measurements with this Josephson detector and this bandwidth will be of 8dB.

This value is sufficient to resolve a pulse structure in the detector response. If the higher dynamic range is required

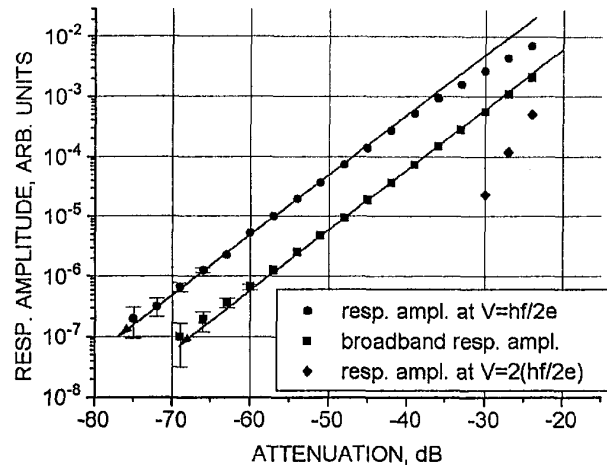


Fig. 4. The amplitudes of Josephson junction responses as a function of incident millimeter-wave radiation intensity.

during the measurements, one can average the signals from serial pulses.

V. CONCLUSIONS

The design of the compact quasioptical detector with Josephson junction and low-noise cryogenic analog electronics is presented.

The noise equivalent power for the frequency-selective response was $7.5 \cdot 10^{-11} \text{ W}/\sqrt{\text{Hz}}$.

The dynamic range of thin film $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ grain-boundary Josephson junction response to the millimeter-wave (86GHz) radiation has been measured. It has been demonstrated, that the dynamic range for the frequency-selective response was 43dB above the noise equivalent power and for the nonselective response at low frequency exceeds 45dB.

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